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Parametric analysis of passive ultra-low energy building envelope performance in existing residential buildings

Hui Fang✉, Wen-Ke Li & Peng Dai

With the proposed goals of "energy conservation, carbon reduction, and green development," green and low-carbon lifestyles have gained significant attention. As a major sector of energy consumption, residential buildings face common issues such as high energy consumption, poor comfort, and aging facilities. Taking a residential building in the West Coast New Area of Qingdao, Shandong Province as a case study, this research employs field surveys and DesignBuilder software simulations to analyze the performance of building envelopes and interior walls in non-heated spaces. The thermal insulation performance differences are compared across three stages: the original building, preliminary retrofit, and passive ultra-low energy stage. On this basis, a parametric analysis of the thermal performance of passive ultra-low energy building envelope components was conducted. The results demonstrate that passive ultra-low energy retrofitting of the building envelope can achieve an energy-saving rate of up to 87.06% compared to the original building, and 84.9% compared to the preliminary retrofit. This research, focusing on the parametric analysis of passive ultra-low energy envelope performance in existing residential buildings, provides a theoretical foundation for energy conservation and carbon reduction in existing residential buildings.

Keywords Existing residential buildings, Building envelope, Passive design, Ultra-low energy consumption, DesignBuilder

In the 1980s, China's Ministry of Urban and Rural Construction and Environmental Protection first promulgated the *design standard for energy efficiency of civil buildings (heating residential buildings)*[1], marking the transition of energy retrofit for existing residential buildings from an initial phase to a systematic and sustained development process. Guided by laws, regulations, and policies, this process aims to systematically reduce building energy consumption and carbon emissions, supporting national goals for green development and energy conservation and emission reduction. Early retrofitting efforts primarily focused on enhancing energy efficiency and seismic performance. With technological advancements and the deepening adoption of green development principles, passive ultra-low energy building[2] has emerged as a comprehensive strategy for building energy retrofit. This strategy not only emphasizes significant reductions in energy consumption but also ensures indoor environmental comfort and improved building quality through performance-based design methods[3,4], thereby driving the transformation of existing residential buildings toward green, low-carbon, and circular development models. Through a series of energy-saving retrofit measures, China is progressively achieving its goals in building-sector energy conservation and emission reduction, laying a solid foundation for achieving carbon peaking in urban and rural construction by 2030. In recent years, both national and Shandong provincial authorities have introduced policy documents on ultra-low energy residential development (Table 1).

The *China Building Energy Consumption and Carbon Emissions Research Report (2023)* reveals that in 2021, the total energy consumption of the entire building lifecycle in China reached 1.91 billion tons of standard coal equivalent, accounting for 36.3% of the nation's total energy consumption[5]. This data underscores the significant role of the building sector in national energy use and carbon emissions. In the same year, statistics from the National Bureau of Statistics during the 13th Five-Year Plan period indicated that the energy-efficient retrofit area for existing urban residential buildings exceeded 1.5 billion m^2 nationwide (Shandong Province: 82.37 million m^2; Qingdao City: 24.47 million m^2). These retrofitting practices have not only improved the energy utilization efficiency of existing residential buildings but also contributed positively to reducing energy consumption and

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Level	Year	Document title	Key contents
National	2015	Technical guidelines for passive ultra-low energy green buildings (residential)	Defined features of ultra-low energy green buildings; established energy consumption and air tightness indicators; provided technical guidance, acceptance criteria, and evaluation standards
	2019	Technical standard for zero energy buildings	Comprehensive regulations for ultra-low energy building technologies, including indoor environmental parameters, energy efficiency metrics, and building air tightness
Shandong	2016	Design standard for passive ultra-low energy residential buildings	Regulated building envelope design, thermal bridge-free design, air tightness design, shading design; provided calculation methods for heating, cooling, and primary energy demand
	2023	Guidelines for high-quality residential development in Shandong (2023)	Promoted refined construction and meticulous management; implemented green and healthy, smart technology, and age-friendly development concepts and standards
Qingdao	2020	Special plan for green buildings and ultra-low energy residential development in Qingdao (2021–2025)	Advanced high-quality development of green buildings, ultra-low energy buildings, and prefabricated buildings; outlined development goals and measures

Table 1. National and Shandong provincial policies and technical guidelines for ultra-low energy residential buildings.

lowering carbon emissions. Consequently, the number of existing residential buildings requiring retrofitting in China remains substantial, demonstrating vast market potential under the impetus of the "Dual Carbon" strategy (carbon peaking and carbon neutrality).

E.Vettorazzi et al. analyzed typical residential buildings in different climatic zones of Brazil and concluded that adopting passive energy-saving technologies could reduce energy demand by 83.5, 56.3, and 55.1%, respectively[6]. Yang Peisen investigated a passive ultra-low energy residential building and found that compared to a building with 75% energy savings, the passive technology achieved an energy-saving rate of 90%, saving approximately 28 tons of coal annually[7]. Song Guoao conducted a study on a residential building through passive ultra-low energy retrofit simulations, demonstrating a reduction in lifecycle heating energy consumption by 8.6 million kWh and operational cost savings of 7.44 million RMB, with an energy-saving rate exceeding 82.7%[8]. Chen Yibo et al. analyzed the Passive House retrofit project in Suzhou Tonglihu Jiayuan, highlighting that precision construction, performance-based design, and digital management optimized energy demand while ensuring air tightness, thermal insulation quality, and efficient lifecycle monitoring and operation[9]. Fu Xin designed an ultra-low energy building using strategies such as intermittent zonal operation, shading optimization, and energy consumption control, achieving a 61% reduction in annual air conditioning electricity consumption compared to passive houses, while providing a more comfortable indoor environment tailored to local residents' habits and comfort needs[10]. Wei Yuanyuan summarized common passive energy-saving technologies and their applications, analyzed three case studies, and proposed strategies in two key areas: procedural frameworks (including feasibility studies, design phases, and post-occupancy evaluations) and methodological frameworks (e.g., optimized design, technology integration, and low-cost strategies), aiming to provide practical references for future building retrofit[11].

As of the end of 2024, only 56 passive ultra-low energy buildings in China are listed in the Passive House Database (Passive House Institute), with just one retrofitted existing residential building. A keyword search for "ultra-low energy retrofit" in the China National Knowledge Infrastructure (CNKI) database yielded 231 valid papers after excluding technical reports and conference literature. Further filtering with keywords "existing residential buildings," "ultra-low energy retrofit," and "residential" identified 14 valid papers, accounting for only 6.01% (Fig. 1). These findings indicate significant gaps in research on ultra-low energy retrofit of existing residential buildings in China, underscoring the urgent need for systematic technical pathway exploration[12].

This study combines existing residential building case studies with ultra-low energy building technologies to conduct simulation-based validation. Focusing on the building envelope and interior walls in non-heated spaces, the research investigates differences in thermal insulation performance across three stages: the original building, preliminary retrofit, and passive ultra-low energy retrofit. Through quantitative analysis of the energy-saving efficiency of the building envelope, the study proposes passive ultra-low energy retrofit strategies.

China's pre-2000 building stock totals approximately 4.215 billion m^2, with structures built between 1974 and 2000 accounting for 70% of this stock[13]. These buildings are predominantly masonry structures lacking thermal insulation measures and exhibiting poor air tightness, resulting in high building energy consumption[14,15]. Following the 1998 State Council issuance of the *Notice on Further Deepening Urban Housing System Reform and Accelerating Housing Construction*, the proportion of commercial residential buildings among urban completed housing surged from 32% in 1995 to over 70% by 2007. Concurrently, national policies on building energy efficiency and financial subsidies created favorable conditions for energy efficiency retrofit of residential buildings during this period[16]. Therefore, this study focuses on residential buildings constructed between the 1990s and early 2000s, analyzing their current conditions and summarizing prevalent issues (Table 2).

The residential community is located in the West Coast New Area of Qingdao, Shandong Province, classified as a cold climate zone (per Chinese climate zoning standards). Constructed in 2003, the development adopts an east–west orientation layout and comprises 69 buildings categorized into five design typologies (Fig. 2). Type A buildings, accounting for 36.2% of the total (25 buildings), are oriented between 15° southeast and 15° southwest, with dual-unit layouts per staircase core and a unit area of 192 m^2. Due to their largest building envelope area and highest exterior exposure, Type A buildings exhibit the poorest thermal insulation performance, making them the focus of thermal performance simulation analysis.

The residential community underwent external wall insulation panel retrofit from November 2013 to May 2014. For this study, buildings before retrofit are defined as the original building, while those post-retrofit (without interior modifications) are termed preliminary retrofit. To minimize construction-related variability, annual

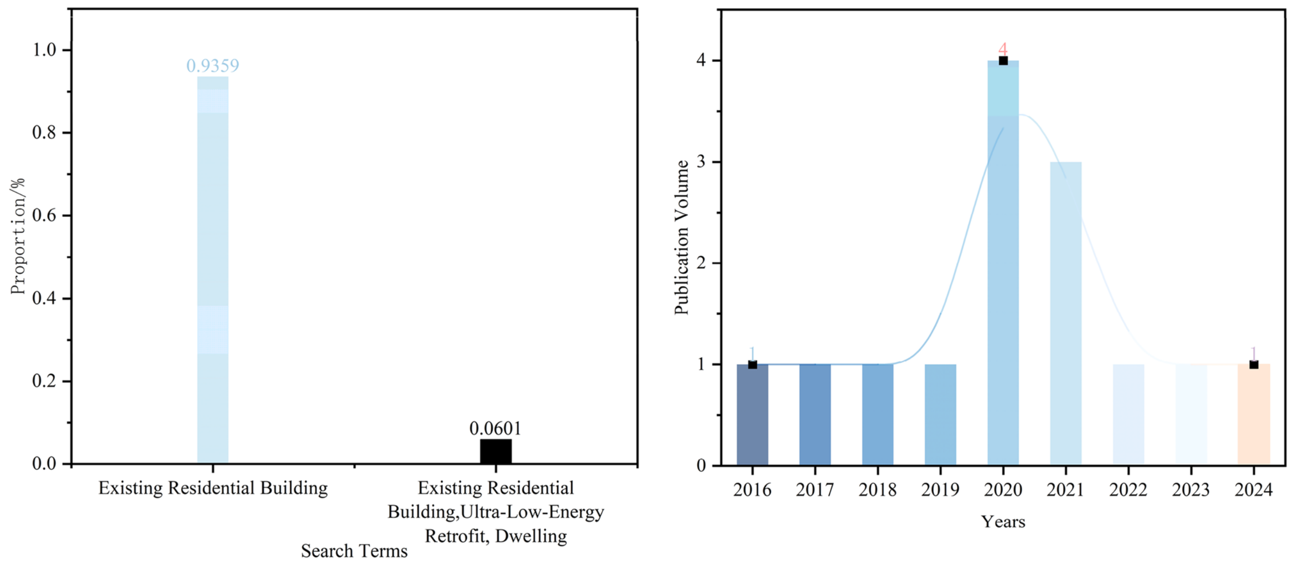

Fig. 1. Proportion of "existing residential buildings, ultra-low energy retrofit, and residential buildings" and annual publication volume.

	Component	Existing issues
Exterior	Exterior walls	240 mm thick solid clay bricks with exposed brickwork or painted/tiled finishes; no insulation or poor thermal performance
	Windows	Steel-framed single-glazed windows with poor air tightness and high thermal transmittance (U-value); some replaced with double-glazed windows but still insufficient insulation
	Roof	Reinforced concrete slabs with no insulation layer; some retrofitted with insulation or ventilated insulation layers, but thermal performance remains inadequate
Interior	Partition walls	120 or 240 mm thick solid clay bricks with low thermal resistance
	Entrance doors	Predominantly steel doors with poor thermal insulation performance

Table 2. Overview of existing issues in existing residential buildings.

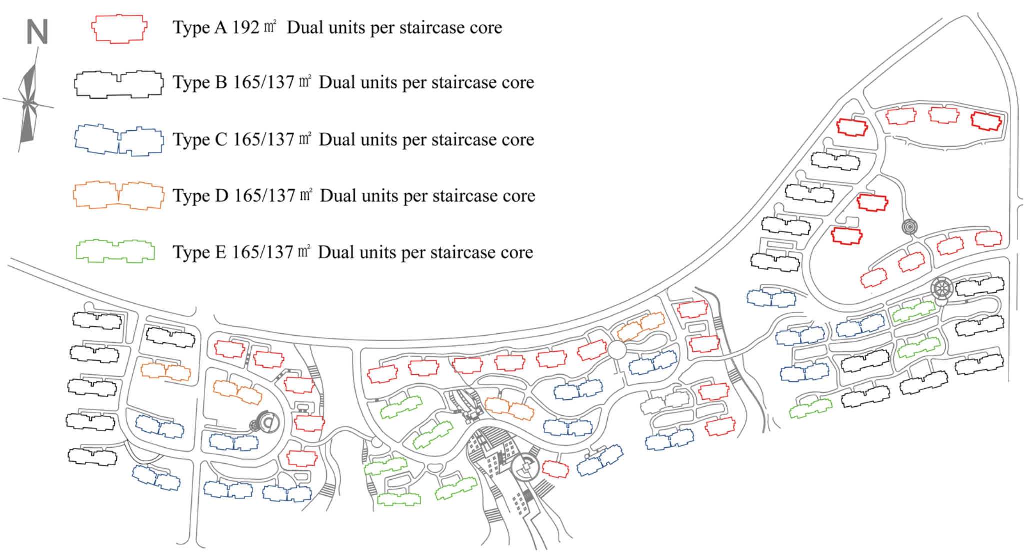

Fig. 2. Distribution of residential block layouts.

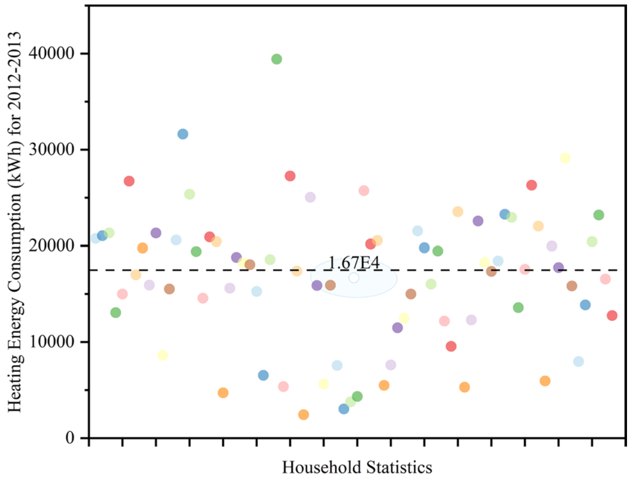

Fig. 3. Annual heating consumption (original building).

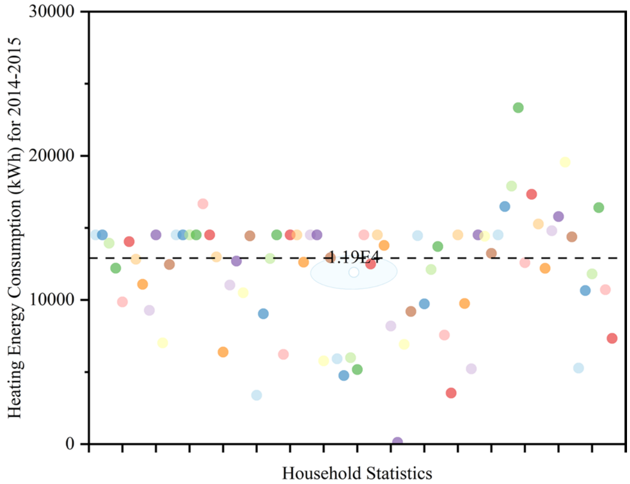

Fig. 4. Heating consumption (preliminary retrofit).

heating energy consumption data from 78 households were collected for both pre-retrofit (2012–2013) and post-retrofit (2014–2015) periods (Figs. 3, 4).

- Original building: Annual heating energy consumption ranged from 2,449 to 39,423 kWh per household, with an average of 16,696.79 kWh.
- Preliminary retrofit: Consumption ranged from 3,390 to 23,344 kWh, averaging 11,922.26 kWh.

Compared to the original building, the preliminary retrofit achieved an energy-saving rate of 28.6%; however, 49 households still exceeded the average consumption. These results indicate that retrofit only external wall insulation panels failed to meet the ≥ 50% energy-saving rate required by the Technical Code for Energy Efficiency Retrofit of Existing Residential Buildings (JGJ/T 129–2015), necessitating further retrofitting measures.

Methodology

Model development

Due to its notable strengths in user-friendliness, accuracy, and visualization capabilities compared to EnergyPlus, DesignBuilder (Version 7.0.2.006, https://www.designbuilder.co.uk) was selected for the building energy consumption simulation analysis[17].

Case study parameters (type A building):

- Building configuration: 5-story residential structure.
- Total floor area: 2,392.4 m^2.
- Floor height: 3 m.
- Shape coefficient: 0.31.

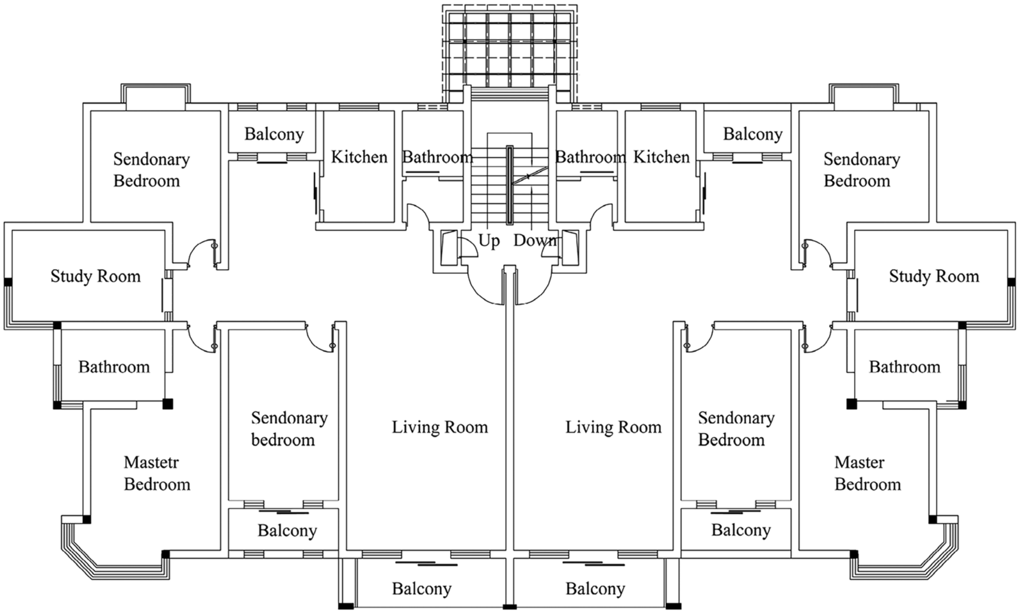

Fig. 5. Standard floor plan.

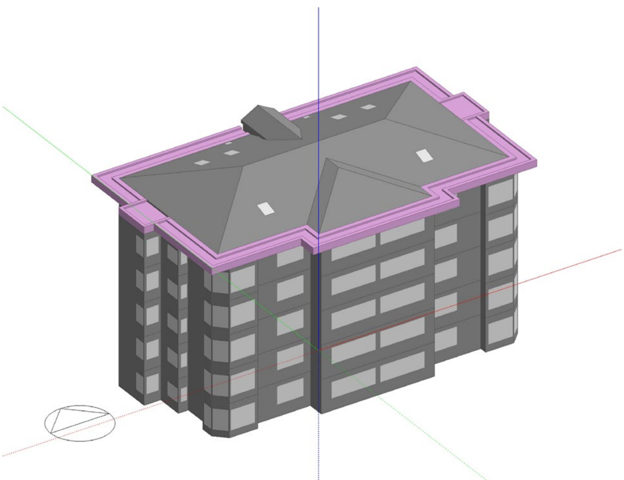

Fig. 6. DesignBuilder model.

- Orientation: True south.
- Window-to-wall ratio (WWR): North 0.45, South 0.43, East/West 0.13.

The standard floor plan and DesignBuilder model are illustrated in (Figs. 5, 6), respectively.

Parameter determination

The thermal performance of the building envelope is a critical factor influencing building energy consumption. Key parameters such as thermal transmittance (U-value) and air tightness must be scientifically determined based on climatic conditions and retrofit objectives. This study references the EnerPHit standard (Germany)[18] for passive retrofit of existing buildings (N_{50}(Air Changes per Hour at 50 Pascals pressure difference,ACH@50 Pa) ≤ 1.0 ACH) and integrates the air tightness limit for new buildings from the Shandong Provincial Design Standard for Passive Ultra-Low Energy Residential Buildings (N_{50} ≤ 0.6 ACH). Considering technical challenges such as structural aging and crack treatment in existing residential buildings, the air tightness parameter was set to 0.6–1.5 ACH under N_{50} conditions, balancing energy-saving effects and the feasibility of energy-saving construction techniques. To achieve the targeted low airtightness level, the retrofit process should incorporate the following systematic measures:

Component	Area	Structural composition (from interior to exterior)	U-value [W/(m²·K)]	SHGC
Exterior walls	1123.34 m²	20 mm cement mortar + 240 mm perforated clay brick + 20 mm plaster mortar + 20 mm cement mortar	0.949	–
Roof	283.967 m²	100 mm reinforced concrete + 20 mm lime-cement mortar + 35 mm extruded polystyrene (XPS) board + 30 mm cement mortar	0.85	–
Windows	378.135 m²	Thermal break aluminum alloy window with single-layer insulating glass (5 mm + 9 mm air gap + 5 mm)	3.0	0.67

Table 3. Original building envelope structure.

Component	Area	Structural composition (from interior to exterior)	U-value [W/(m²·K)]	SHGC
Exterior walls	1123.34 m²	20 mm cement mortar + 240 mm perforated clay brick + 20 mm cement mortar + 60 mm expanded polystyrene (EPS) board + 20 mm cement mortar	0.6	–
Roof	283.967 m²	100 mm reinforced concrete + 20 mm lime-cement mortar + 35 mm extruded polystyrene (XPS) board + 30 mm cement mortar	0.85	–
Windows	378.135 m²	Thermal break aluminum alloy window with single-layer insulating glass (5 mm + 9 mm air gap + 5 mm)	3.0	0.67

Table 4. Preliminary retrofit of building envelope.

1. Employ high-performance airtight membranes combined with specialized sealing tape or sealant paste to provide continuous sealing at critical leakage points, including window and door openings, pipe penetrations, and envelope joints.
2. Perform structural repairs to remedy existing cracks.
3. Conduct periodic blower-door testing to detect airtightness deficiencies and implement corrective actions dynamically.

The heating season was defined as November 16 to April 10 annually, following Shandong standards. Meteorological data were sourced from Qingdao Liuting Airport Meteorological Station. The thermal performance parameters of the building envelope, including the thermal transmittance of external walls and the type of glazing systems, were specified for both the original building and the preliminary retrofit scheme. All parameters were defined and implemented within the DesignBuilder simulation environment. Boundary conditions such as soil thermal conductivity (1.73 W/m·K) and ground thermal absorptivity (0.9) were configured based on Qingdao's geological characteristics, with reference to typical values in the Building Climate Zoning Standard (GB 50178) and Shandong Provincial Code for Geotechnical Engineering Investigation to ensure regional applicability of the simulations.

Heating energy consumption analysis of the building envelope

Under the N_{50} standard, the air change rate (ACH) was set to 1.0 ACH to compare heating energy consumption between the original building and preliminary retrofit stages. The DesignBuilder model parameters for the building envelope are detailed in (Tables 3, 4).

- Original building: Simulated annual heating energy consumption = 114,128.88 kWh.
- Preliminary retrofit: Simulated annual heating energy consumption = 99,341.09 kWh, yielding an energy-saving rate of 12.9%.

This result is significantly lower than the ≥ 50% energy-saving rate mandated by the Technical Code for Energy Efficiency Retrofit of Existing Residential Buildings (JGJ/T 129–2012), indicating that the preliminary retrofit scheme requires further improvement in envelope performance to enhance the thermal insulation performance of the building envelope.

Further analysis of heating energy consumption differences under the N_{50} standard reveals that reducing the air change rate (ACH) from 1.5 to 0.6 ACH significantly impacts energy demand:

- Original building:
    - o Heating energy consumption decreased from 159,466.02 kWh to 78,060.75 kWh, with a 51.04% reduction (Fig. 7).
    - o The monthly energy variation rate increased from 6% to 11.4%.
- Preliminary retrofit:
    - o Heating energy consumption dropped from 144,611.9 kWh to 63,520.4 kWh, achieving a 56.07% reduction (Fig. 8).
    - o The monthly energy variation rate rose from 6.7 to 13.9%.

The simulations demonstrate that reducing air change rates effectively lowers building energy consumption. Notably, after preliminary retrofit, improvements in air tightness had a more pronounced impact, with a 57.06% decline in heating energy consumption.

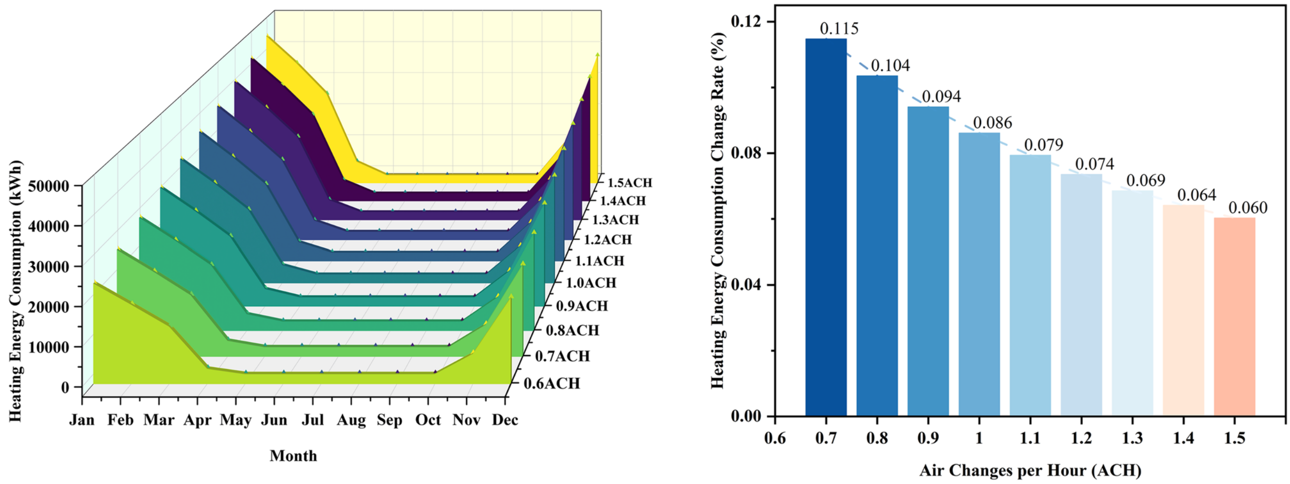

Fig. 7. Monthly heating energy consumption (original building) and heating energy consumption change rate.

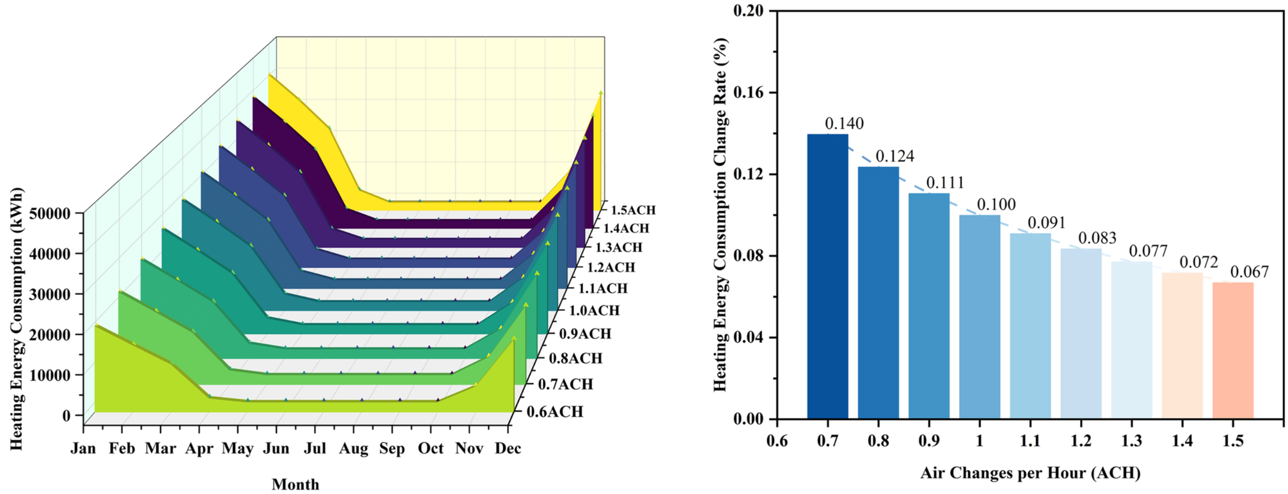

Fig. 8. Monthly heating energy consumption (preliminary retrofit) and heating energy consumption change rate.

The results indicate that the energy-saving effects of the preliminary retrofit for existing residential buildings are constrained by insufficient thermal insulation performance and air tightness of the building envelope, with air change rate (ACH) variations significantly impacting energy consumption. To bridge the gap with the energy efficiency targets outlined in the Technical Standard for Nearly Zero-Energy Buildings, it is imperative to implement passive ultra-low energy retrofit strategies for the building envelope. This entails enhancing thermal performance metrics (e.g., U-values, airtightness) and exploring retrofit pathways adapted to cold climate characteristics, thereby achieving alignment with ultra-low energy standards.

Passive ultra-low energy retrofit strategies

Combining field surveys and simulation analyses, the preliminary retrofit of existing residential buildings achieved an energy-saving rate of 12.9%, which falls significantly short of the 60% target outlined in the Technical Standard for Nearly Zero-Energy Buildings. To address this gap, passive ultra-low energy retrofit strategies for the building envelope are proposed, referencing the EnerPHit standard and Shandong Provincial Technical Guidelines. These strategies include:

Reconstructing the building envelope with high-performance insulation materials (Table 5).

Reducing the air change rate to $N_{50} \leq 0.6$ ACH.

A quantitative analysis of heating energy consumption was conducted across three stages: original building, preliminary retrofit, and passive ultra-low energy retrofit. This analysis aims to establish a technical pathway for energy-efficient retrofit of existing residential buildings in cold climate zones, aligning with ultra-low energy goals.

Component	Area	Structural composition (from interior to exterior)	U-value [W/(m²·K)]	SHGC
Exterior walls	1123.34 m²	20 mm cement plaster + 240 mm perforated clay brick + 230 mm expanded polystyrene (EPS) + 20 mm plaster	0.122	–
Roof	283.967 m²	20 mm plaster + 240 mm perforated clay brick + 250 mm extruded polystyrene (XPS) board + 40 mm C20 concrete	0.125	–
Windows	378.135 m²	Triple-glazed low-emissivity (Low-E) glass with warm-edge spacer (5 mm + 18 mm argon gap + 5 mm + 18 mm argon gap + 5 mm)	0.62	0.48

Table 5. Passive ultra-low energy building envelope structures.

Air change rate (ACH)	Retrofit stage	Heating energy consumption (kWh)	Energy-saving rate (%)
1.0 ACH	Original building	114,128.88	–
	Preliminary retrofit	99,341.09	12.9
	Ultra-low energy retrofit	43,099.86	56.6
0.6 ACH	Original building	78,060.75	–
	Preliminary Retrofit	63,520.40	18.6
	Ultra-low energy retrofit	14,953.62	76.5

Table 6. Simulated heating energy consumption results across three stages.

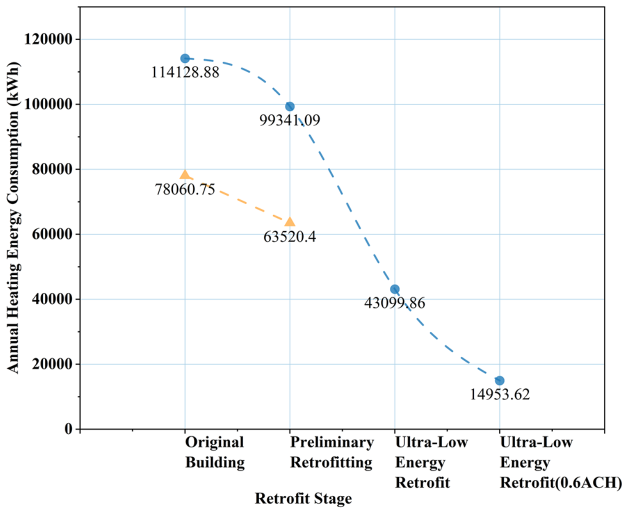

Fig. 9. Simulated heating energy consumption results across three stages.

Analysis of the synergistic energy-saving effects of building envelope retrofit

After implementing passive ultra-low energy retrofit on the building, the annual simulated heating energy consumption at an air change rate (ACH) of 1.0 ACH is 43,099.86 kWh, achieving an energy-saving rate of 62.2% compared to the original building, with an annual heating energy cost reduction of 12,074.9 CNY. Compared to the preliminary retrofit, the energy-saving rate is 56.6%, reducing annual heating costs by 9,561 CNY. When the air change rate is further reduced to 0.6 ACH, the annual heating energy consumption drops to 14,953.62 kWh, yielding an energy-saving rate of 86.9% compared to the original building and a cost reduction of 16,859.8 CNY. Compared to the preliminary retrofit, the energy-saving rate reaches 76.5%, with a cost reduction of 8,256.4 CNY (Table 6, Fig. 9).

The simulation results demonstrate a significant downward trend in heating energy consumption with reduced air change rates, confirming that improved air tightness is the primary technical driver for lowering energy demand. Notably, the ground floor exhibits significantly higher heating energy consumption than other floors, highlighting the necessity of enhancing the thermal performance of the building envelope. Extending the insulation layer downward to mitigate thermal bridging effects at the ground floor will be a critical direction for advancing ultra-low energy retrofit.

Sensitivity analysis of air tightness parameter range on heating energy consumption

Referencing the German EnerPHit standard and Shandong Provincial Local Standards, the air change rate (ACH) was set to 1.5–0.6 ACH under N_{50} conditions. After implementing ultra-low energy retrofit of the building envelope, the variation rate of heating energy consumption increased from 10.9 to 42.3%, while the heating energy consumption decreased from 83,296.76 kWh to 14,953.62 kWh, achieving a 82.04% reduction (Fig. 10).

The simulations reveal that reducing the air change rate significantly lowers heating energy consumption, while the energy variation rate exhibits an upward trend. At low air change rates (e.g., 0.6 ACH), heat transfer losses dominate, and building envelope retrofit effectively reduces energy demand, resulting in a higher energy variation rate (42.3%). Conversely, at high air change rates (e.g., 1.5 ACH), ventilation losses become the primary factor, leading to reduced energy-saving effectiveness and a relatively low variation in heating energy consumption (10.9%).

Gradient energy-saving characteristics of downward-extended external insulation

To ensure continuity of the insulation layer and optimize indoor thermal performance on the ground floor, the external insulation of ultra-low energy buildings is typically extended downward below the frost depth. According to data from the Shandong Meteorological Bureau, the minimum frost depth in Qingdao's West Coast New Area is 320 mm.

Ground heat transfer simulation methodology:

- Employed the EnergyPlus Kiva Basic Foundation module for 3D transient ground heat transfer calculations
- Ground floor adjacent to outdoor soil

Simulation boundary conditions:

- The ground floor is adjacent to outdoor soil.
- Indoor temperature: 18 °C
- Soil thermal conductivity: 1.73 W/(m·K)
- Soil density: 1,842 kg/m^3
- Soil specific heat capacity: 419 J/(kg·K)
- Ground solar absorptivity: 0.9
- Ground thermal absorptivity: 0.9
- Surface roughness: 0.03 m

In the DesignBuilder model, four scenarios of external insulation downward extension were simulated: 300, 600, 900, and 1200 mm, combined with air change rates (ACH) of 0.6, 0.8, and 1.0 ACH. Based on Qingdao's frost depth (320 mm) and winter outdoor conditions, the above-ground wall height was set to 300 mm, and the sub-floor wall depth to 800 mm.

Simulation Results (Table 7):

- Ground floor: Heating energy consumption decreased by 5.02% (607.51 kWh) to 10.09% (514.17 kWh).
- Second floor: Heating energy consumption decreased by 0.45% (31.70 kWh) to 1.06% (22.23 kWh).

These findings highlight the gradient energy-saving benefits of extending external insulation below the frost line, particularly for mitigating ground-floor thermal bridging.

By extending the external insulation layer downward below the frost line, the heating energy consumption of the ground floor can be effectively reduced by 5.02%–10.09%, with energy-saving benefits being more pronounced under lower air change rates (ACH). However, given the limited impact on the second-floor heating energy consumption, the optimal insulation extension depth should be determined based on ground-floor

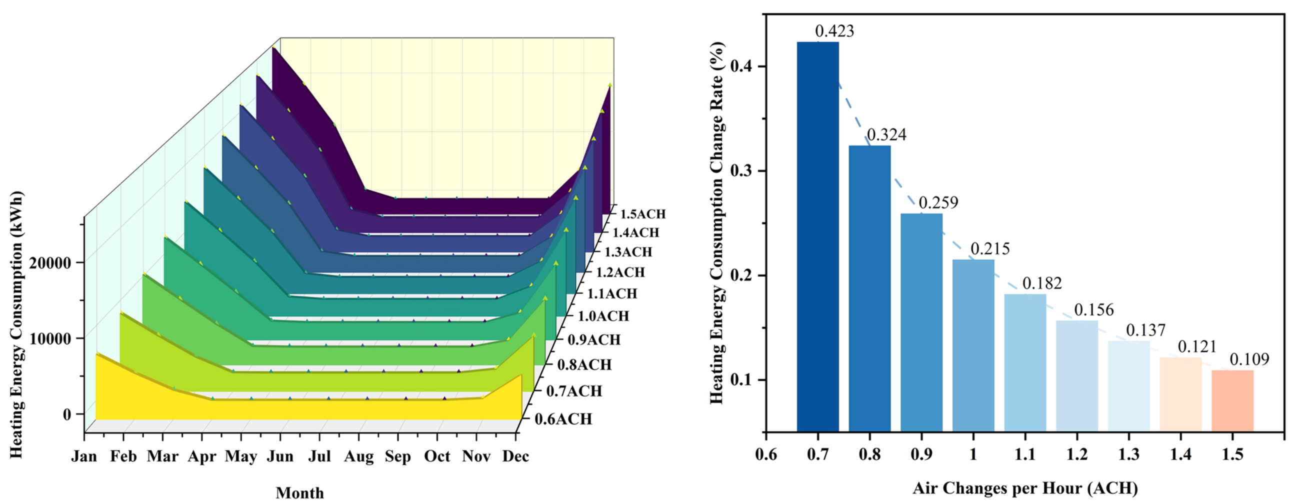

Fig. 10. Monthly heating energy consumption (ultra-low energy retrofit) and heating energy consumption change rate.

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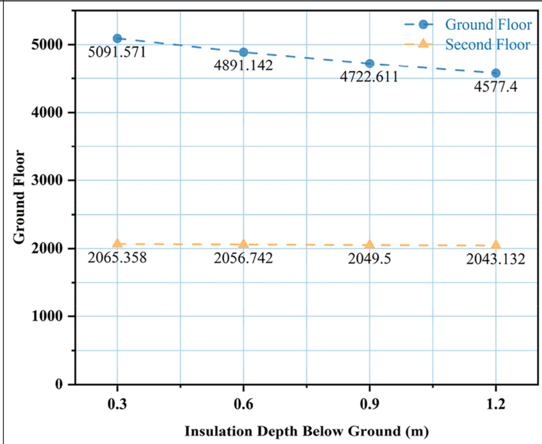
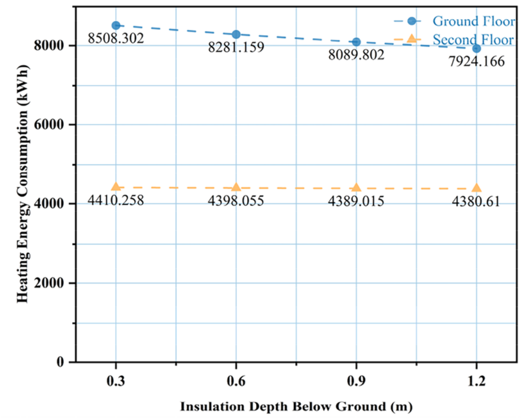
<tr><th>Air changes per hour (ACH)</th><th>Heating energy consumption comparison</th><th>Reduction rate</th></tr>
<tr><td>0.6</td><td>
</td><td>1.06% ~ 10.09%</td></tr>
<tr><td>0.8</td><td>
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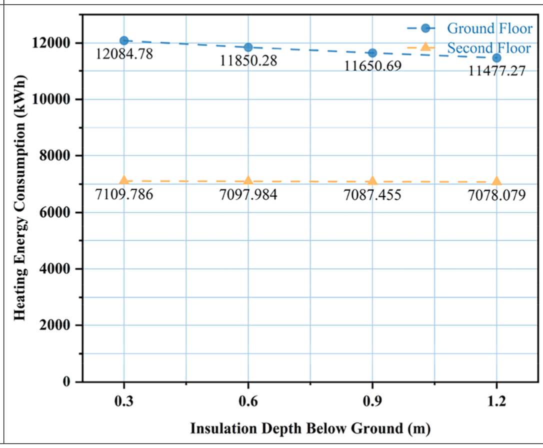
<tr><td>1</td><td>
</td><td>0.45% ~ 5.02%</td></tr>
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Table 7. Heating energy consumption and reduction rates after downward extension of external insulation.

energy-saving requirements and cost-benefit balance during practical retrofit. This approach ensures optimal resource allocation and maximization of energy-saving benefits.

Synergistic effects of retrofit non-heated space partition walls and entrance doors on heating energy consumption

In the further retrofit of passive ultra-low energy building envelopes in existing residential buildings, non-heated space partition walls (primarily interior partitions and party walls) and entrance doors represent two typical thermal weak points, with significant differences in their energy-saving potential and synergistic effects. Since this study focuses on simulating the heating energy consumption of the entire building, the two individual residential units were integrated into a single thermal zone to streamline the modeling process and capture the overall thermal performance more effectively, the thermal zone of Prototype A is illustrated as shown in the figure below (Fig. 11).

1. Zone 1 (unconditioned core area) occupancy:

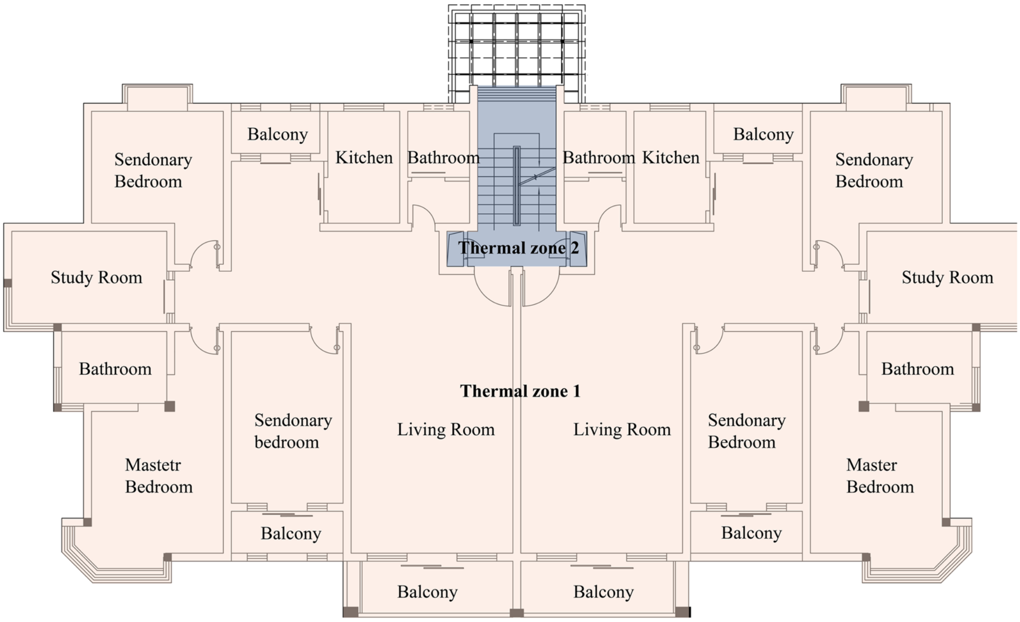

Fig. 11. Thermal zone division.

Zone ID	Function	Heating setpoint/setback(℃)	Cooling setpoint/setback (℃)	Occupancy hours	Description
Zone 1	Unconditioned core area	0.0/6.0	30.0/30.0	4.5	Includes staircase and ventilation shaft
Zone 2	Occupied residential zone	18.0/12.0	25.0/28.0	10.95	Two households per floor; treated as a single residential zone

Table 8. Thermal zones and corresponding temperature settings.

- This zone was assumed to be partially occupied (occupancy fraction = 0.3) from 07:30 to 22:30 daily.
- This resulted in an average occupancy duration of 4.5 h/day (Table 8).

2. Zone 2 (occupied residential zone) occupancy:

- This zone followed a more dynamic occupancy pattern:
  - Partial occupancy (occupancy fraction = 0.3) during 07:30–09:30 and 18:00–22:30.
  - Full occupancy overnight between 22:30 and 07:30.
- The resulting average occupancy duration was approximately 10.95 h/day (Table 8).

Analysis of energy-saving potential for non-heated space partition wall retrofit

The Type A partition walls consist of 240 mm brick walls with a thermal transmittance (U-value) exceeding the current code limit (≤ 1.5 W/(m^2·K)). Simulation experiments involving the addition of expanded vitrified microsphere insulation layers revealed that under air change rates (ACH) of 0.6–1.0 h^{-1}, increasing the insulation thickness from 10 to 100 mm reduced heating energy consumption by only 50–140 kWh. Furthermore, the retrofit of partition walls is constrained by wall area limitations (340.2 m^2) and safety evacuation corridor width requirements, resulting in limited energy-saving efficacy (Table 9). Therefore, the economic feasibility and practicality of retrofit non-heated space partition walls must be comprehensively evaluated in ultra-low energy envelope retrofit strategies, considering spatial utilization and compliance with fire safety codes.

Synergistic energy-saving effects of entrance door retrofit

The thermal transmittance (U-value) of the Type A entrance door (> 1.3 W/(m^2·K)) fails to meet energy efficiency requirements. After replacing it with a certified passive ultra-low energy door, the annual simulated heating energy consumption was reduced to 14,767.29 kWh under an air change rate of 0.6 h^{-1}. This corresponds to an energy-saving rate of 87.06% compared to the original building, with an estimated annual heating cost reduction of 16,891.5 CNY. Under an air change rate of 0.8 h^{-1}, the annual simulated heating energy consumption increased to 27,192.18 kWh, resulting in an energy-saving rate of 76.17% and a heating cost reduction of 14,779.3 CNY.

Insulation thickness(m)	Heating energy consumption (kWh) at 0.6 ACH	Heating energy consumption (kWh) at 0.8 ACH	Heating energy consumption (kWh) at 1 ACH
0.01	14,898.51	28,134.46	43,015.27
0.02	14,890.45	28,128.12	43,012.67
0.03	14,882.90	28,115.78	43,008.34
0.04	14,875.56	28,103.45	43,001.89
0.05	14,868.23	28,092.34	42,994.23
0.06	14,860.89	28,080.67	42,987.56
0.07	14,852.34	28,068.89	42,980.12
0.08	14,845.67	28,056.23	42,972.45
0.09	14,838.12	28,051.90	42,963.78
0.10	14,833.57	28,047.65	42,960.25

Table 9. Heating energy consumption and thickness of expanded vitrified microsphere insulation.

Air changes per hour	Heating energy consumption (kWh)
0.6ACH	14,767.29
0.8ACH	27,192.18
1ACH	42,792.31

Table 10. Heating energy consumption after energy-efficient entrance door retrofit.

When the air change rate reached 1.0 h^{-1}, the simulated annual heating energy consumption rose to 42,792.31 kWh, corresponding to an energy-saving rate of 62.51% and a cost reduction of 12,127.2 CNY. Furthermore, under consistent air change rates ranging from 0.6 to 1.0 h^{-1}, heating energy consumption decreased by 186.33 kWh to 307.54 kWh (Table 10). Comparative analysis reveals that door retrofit achieves 167 kWh higher energy savings than retrofit partition walls with 100 mm expanded vitrified microsphere insulation. This disparity arises because entrance doors act as air tightness weak points in buildings, and improving their thermal performance effectively mitigates cold air infiltration and heat loss. Simulations demonstrate that prioritizing energy-efficient entrance doors with U-values ≤ 1.3 W/(m^2·K) in cold climate residential buildings achieves higher energy efficiency while avoiding complex partition wall retrofit.

In cold climate zones, retrofit with ultra-low energy passive doors yields superior energy-saving efficiency compared to modifying non-heated space partition walls with expanded vitrified microspheres. By integrating passive ultra-low energy retrofit of the building envelope and upgrading entrance doors to ultra-low energy passive doors (U-value ≤ 1.3 W/(m^2·K)), higher energy efficiency can be achieved, reducing cold air infiltration and heat loss while minimizing the need for complex partition wall retrofit. This strategy prioritizes thermal performance enhancement at critical air tightness weak points, aligning with cost-effective and high-impact pathways for ultra-low energy building retrofit.

Conclusions

Through a case study of an existing residential building in Qingdao, Shandong Province, this research analyzed the thermal performance differences across three stages: the original building, preliminary retrofit, and passive ultra-low energy retrofit. The energy-saving efficacy was found to be influenced by the following factors (ranked by contribution): building envelope retrofit > downward extension of external insulation > passive door retrofit > expanded vitrified microsphere insulation. Among these, the improvement in building envelope airtightness (achieved by reducing the air change rate, ACH, to 0.6 h^{-1}) was identified as a key factor in achieving significant energy savings. In comparison to other parameters, enhancing airtightness substantially reduced air infiltration, thus minimizing heat loss and significantly improving the building's thermal retention capacity. This reduction in heat loss was a crucial contributor to the overall reduction in heating energy consumption. Based on these findings, passive ultra-low energy retrofit strategies for existing residential building envelopes are proposed. Key results include:

1. Triple-glazed low-emissivity (Low-E) windows with warm-edge spacers and dual argon-filled cavities, 230 mm expanded polystyrene (EPS) wall insulation, and 250 mm extruded polystyrene (XPS) roof insulation reduced the air change rate (ACH) to 0.6 h^{-1}:

   o Heating energy-saving rate: 86.9% compared to the original building, with annual heating cost savings of 16,859.8 CNY.
   o Heating energy-saving rate: 84.9% compared to preliminary retrofit, with annual heating cost savings of 13,345.9 CNY.

2. Extending external wall insulation downward by 300–1,200 mm reduced ground-floor heating energy consumption by 607.51–514.17 kWh and second-floor consumption by 31.71–22.23 kWh.

3. Upgrading entrance doors to ultra-low energy passive doors (U-value ≤ 1.3 $W/(m^2 \cdot K)$) at 0.6 ACH:

    - Heating energy reduction: 186.33 kWh.
    - Heating energy-saving rate: reaching 87.06% compared to the original building, with annual heating cost saving of 16,891.5CNY.

Thus, passive ultra-low energy retrofit—through high-performance insulation materials, energy-efficient windows, downward-extended wall insulation below the frost line, and reduced air change rates (0.6 ACH)—achieves an 86.9% reduction in heating energy consumption. Retrofitting non-heated space partition walls and entrance doors should be selectively implemented based on cost-benefit analysis. This study provides theoretical foundations and technical pathways for ultra-low energy retrofit of existing residential buildings in cold climates, contributing to national goals of energy conservation, carbon reduction, and green development.

Therefore, during the passive ultra-low energy retrofit of building envelopes in existing residential buildings, the use of high-performance insulation materials, replacement with energy-efficient windows, and downward extension of external wall insulation below the frost line, combined with reducing the air change rate (ACH) to 0.6 h^{-1}, achieves a significant 86.9% reduction in heating energy consumption. For retrofitting measures such as non-heated space partition walls and entrance doors, selective implementation should be prioritized based on site-specific conditions. This study provides theoretical foundations and technical pathways for ultra-low energy retrofit of existing residential buildings in cold climates, offering valuable insights for achieving national goals of energy conservation, carbon reduction, and green development in the building sector.

Data availability

Some or all data, models that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Fang Hui (Corresponding Author): Conceptualization, Resources, Supervision, Methodology, Writing—Review & Editing, Funding Acquisition. Li Wenke: Methodology, Software, Visualization, Writing—Original Draft, Data Curation, Formal Analysis, Investigation. Dai Peng: Conceptualization, Data Curation, Supervision, Validation, Writing—Review & Editing. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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